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STUDIES OF VOLATILES AND ORGANIC MATERIALS IN EARLY TERRESTRIAL AND PRESENT-DAY OUTER SOLAR SYSTEM ENVIRONMENTS

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This report constitutes a review and partial summary of individual projects within several areas of research generally involving the origin, distribution, chemistry, and spectral/dielectric properties of volatiles and organic materials in outer solar system and early terrestrial environments. Other collaborators play a prominent role in some of these studies, as indicated in the references for specific topics.

Impact delivery of volatiles and organic compounds to the early terrestrial planets.

Cometary delivery of organic molecules to the early Earth. Here (Chyba *et al.* 1990) we assess with a state-of-the-art smooth particle hydrodynamic code the survivability of the organic carbon complement of asteroids and comets during the latter part of the heavy bombardment, 4.5 Gyr to 3.8 Gyr ago. Our characterizations of the impactor flux and size distribution show that most of the mass is contributed by large impactors whose organic complement cannot survive the impact process in a 1-bar atmosphere. However, we show that objects $\lesssim$100 m in radius aerobraked through the ~10-bar CO_2 atmosphere proposed for this period can contribute organic material at a rate $\sim 10^6$–$10^7\,\mathrm{kg\,yr^{-1}}$ that exponentially decreases with a half-life of $\sim 10^8$ yr. Total amounts delivered could then be comparable to the contemporary oceanic (3×10^{12} kg) and total (6×10^{14} kg) terrestrial biomasses. (Fig. 1, 2.)

Exogenous sources of prebiotic organic molecules on the early Earth. In this work (Chyba and Sagan, 1991) we investigate (in addition to the delivery by direct impacts considered above) the contribution of interplanetary dust particles, airbursts, and organic synthesis driven by atmospheric and impact shock waves. We find that the inclusion of additional direct (non-shock) sources increases the delivery rate to $\sim 10^8\,\mathrm{kg\,yr^{-1}}$, comparable to *in situ* production rates (from lightning, coronal discharge, aurorae, etc.) for CO_2 atmospheres with high H_2 abundance. Of potentially much greater importance is the additional energy source provided by the shock waves associated with impacts, which can induce organic synthesis at rates $\sim 10^{12}\,\mathrm{kg\,yr^{-1}}$. At this rate a contemporary biomass is produced every 10^3 yr; even in CO_2-dominated atmospheres the shock-driven rate is comparable to the highest rates possible from other *in situ* sources even from highly reducing atmospheres. Impact processes, directly and indirectly, likely were very important for the geochemical carbon cycle and surface organic inventory through the period leading up to the first known biological activity. (Fig. 3.)

Constraints on terrestrial volatile accretion during the heavy bombardment. Further pursuing associated questions arising from earlier work on impact delivery of volatiles (especially H_2O) to the early terrestrial planets, we investigate (Chyba 1991) the consistency between the elemental composition of Earth's upper mantle and lunar highland material, compared to the contribution we compute from heavy bombardment impacts. The delivery of large amounts of volatiles — in particular, oceanic volumes of H_2O — is consistent with known geochemical constraints. While we point out a critical need for more laboratory measurements of the H_2O content of chondritic material, we show that a nominal model of the impactor flux and composition results in the delivery of sufficient H_2O to account for the present mantle+crust inventory, while contributing quantities of C, N, S, and Cl not exceeding those estimated for the mantle+crust. The abundances of highly siderophilic "noble metals" in Earth's upper mantle are also consistent with the expected flux of late heavy bombardment meteoritic material.

Extraterrestrial amino acids and terrestrial life. In a note (Chyba 1990), we comment on recent work explaining the distribution of extraterrestrial amino acids in sediments near the K-T boundary in terms of accretion of comet-derived interplanetary dust particles associated with a main impact event, and on other work reporting a predominance of L-amino acids in the Murchison meteorite. The additional possibility of shock-production of amino acids *in situ* is raised, and is relevant to the concentration of the paper (Chyba and Sagan 1991) summarized above.

Optical constants measurements.

Optical constants of solid methane. Here (Khare *et al.* 1990) we present results for CH_4 in the VIS-NIR, including measurements of those absorption bands in solid crystalline CH_4 with complex part $k > 10^{-6}$ in the wavelength range 1.10–2.65 μm. Since CH_4 is known to be present on the surfaces of Triton and Pluto and C_2H_6 is a major photochemical product, these materials are probably both major

contributors to the still incompletely-understood reflection spectra of Triton and Pluto. (Similar results for C_2H_6 are soon to be published.)

Spectral classification, chemical processes, and distribution of materials.

Color and chemistry on Triton. Using quantitative multiband spacecraft imaging data, one can identify spectrally distinct units of material, and relate these units to the coupled chemical and volatile transport processes controlling the spectral evolution and deposition of the material. In this work (Thompson and Sagan 1990) we find that Triton's surface can be characterized by 6 major spectral units: (1) lightly colored southern hemisphere cap (SHC) material; (2) a bluish thick frost unit beyond the permanent SHC margin; (3) a thin frost unit incompletely covering the equatorial material; (4) a more strongly colored equatorial unit; (5) extremely bright spectrally neutral units; and (6) units showing anomalous UV or red absorption. We also show that sedimenting photochemical organic dust composed of C_2H_4 and C_2H_2 can be rapidly converted to colored products (over a few Triton seasons), while direct surface modification by magnetospheric electrons and cosmic rays requires much longer times. The chemical evidence would then suggest that more strongly colored units are older, while lightly colored units represent seasonal lag deposits and bright units are younger than a few Triton seasons, an interpretation consistent with the major morphological features of Triton's surface.

Triton's streaks as windblown dust. The encounter of the Voyager 2 spacecraft with Neptune's satellite Triton revealed many "dark" (about 10–20% darker than the adjacent frost) surface streaks in Triton's southern hemisphere, resembling the streaks that are due to windblown dust on Mars. It seems therefore that dust transport by winds in Triton's tenuous atmosphere is required, the main question being the mechanism for raising dust from the surface or sub-surface. The two obvious candidates are geyser-like eruptions and direct lofting by surface winds. We have demonstrated (Sagan and Chyba 1990) that, despite Triton's tenuous ($16 \pm 3\,\mu$bar) atmosphere, low-cohesion grains with diameters of $\lesssim 5\,\mu$m, may be carried into suspension by aeolian surface shear stress, given expected geostrophic wind speeds of $\sim 10\,\mathrm{m\,s^{-1}}$. (The wind velocities needed to lift grains as cohesive as those found on Earth, however, are implausibly high.) For erupting plumes, we show that dust-settling timescales and expected wind velocities yield streak length scales in good agreement with those observed. Both candidate mechanisms therefore seem to be consistent with present observations of Triton.

Radar properties of ice, hydrocarbons, and organic heteropolymers.

Titan and other icy satellites: Dielectric properties of constituent materials and implications for radar sounding. Here (Thompson and Squyres 1990) we assess the state of experimental measurements on the dielectric properties of materials relevant to radar sounding of icy satellites, and especially Titan, in expectation of further ground-based work and of planning for the Cassini spacecraft's radar system. Using straightforward dielectric theory appropriate to each type of material, we present and/or fit available measurements for H_2O ice, polyacetylene, tholins, and hydrocarbon liquids without and with polar solutes. Transmission of any surface lakes or oceans on Titan varies from optically thin to optically thick over centimeter to decimeter wavelength ranges. Using a proposed sounding mode for a Cassini radar system, only surface reflections will result at 2.2 cm wavelength, while the sub-liquid layers can be sounded at 13.6 cm. Further, both the ocean-sediment and organic sediment-H_2O ice boundaries could be detected. (Fig. 4.)

References.

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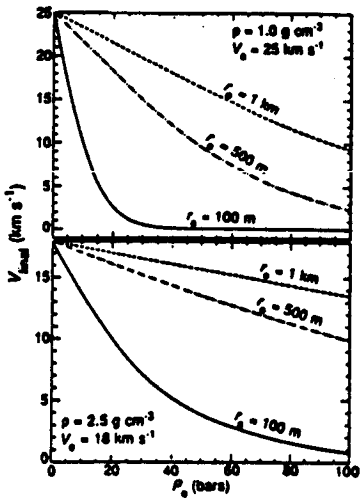

Fig. 1. Impact velocities as a function of surface atmospheric pressure for generic cometary and chondritic impactors at an incidence angle of 0° with radii of 100, 500, or 1000 m. In this illustrative model, the atmosphere is equivalent to the contemporary terrestrial one, with a surface pressure increased to P_s.

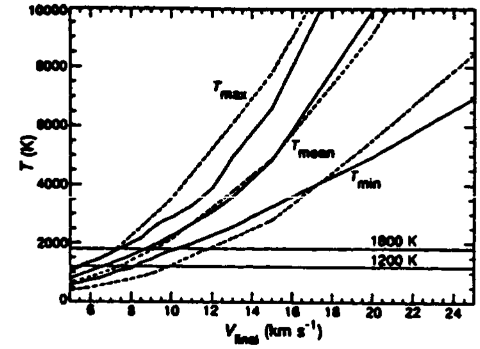

Fig. 2. Maximum, minimum, and mean temperatures for a comet impacting an ocean 3 km deep. The results here are independent of comet radius, provided the ocean is at least several cometary radii deep. The dotted lines denote temperatures obtained from the Tillotson EOS with an assumed constant specific heat capacity for ice. The solid lines represent temperatures from Sesame EOS. The temperatures 1800 and 1200 K are the temperatures for which HCN and simple organics (such as short-chain aliphatics, benzene, and H_2CO), respectively, survive shock heating for time scales comparable with those of impact. For impact velocities ≤ 10 km s^{-1}, a significant fraction of the organic inventory survives impact.

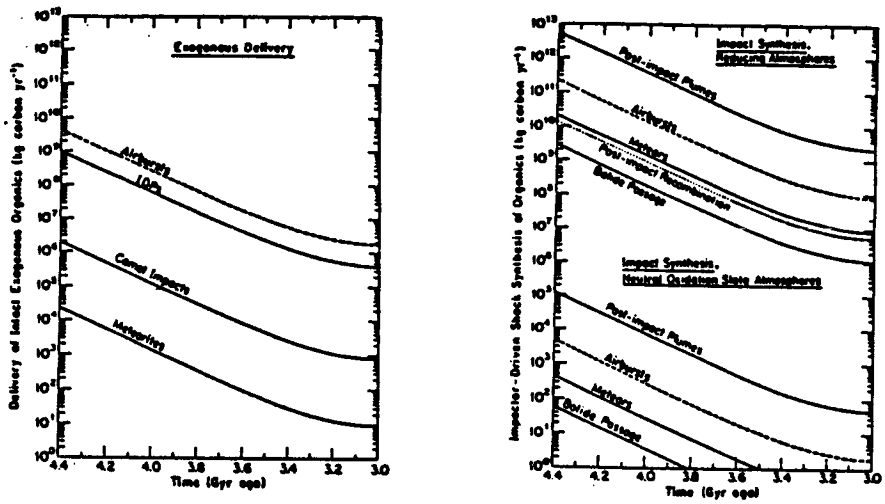

Fig. 3. Exogenous organic carbon provided to Earth as a function of time, from (a) sources delivering intact extraterrestrial organic molecules, and (b) impactor-driven shock synthesis of organics in the terrestrial atmosphere or post-impact vapor plume. Curves are labelled according to source. In (b), the upper curves are for CH_4+ (NH_3/N_2) + H_2O reducing atmospheres, and the lower curves are for CO_2+ N_2+ H_2O neutral oxidation state atmospheres. Solid lines represent the more secure estimates. Dashed lines indicate upper bounds, and the dotted line denotes an estimate that, while uncertain, is largely independent of the oxidation state of the atmosphere.

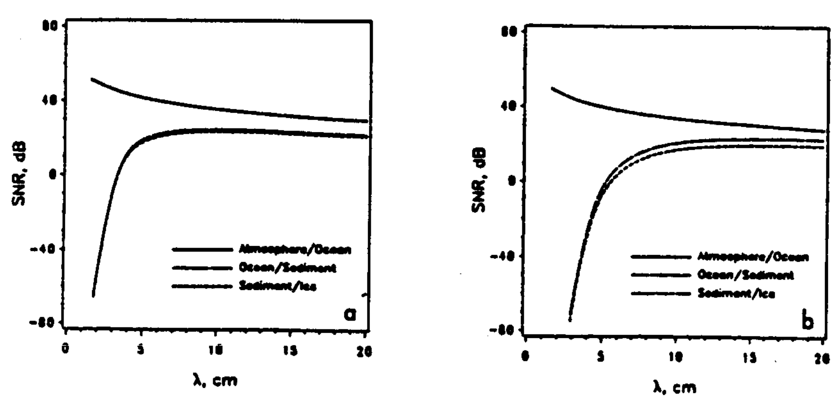

Fig. 4. Calculated signal to noise ratio (SNR) vs wavelength for radar sounding using a possible Cassini mission radar system in a 1000-km flyby of Titan. (a) low-CH_4 (X_{CH_4} = 0.058); (b) high-CH_4 (X_{CH_4} = 0.81). (See Table V.) Curves show the SNR for reflections from the upper surface of the ocean, the ocean/solid organics interface, and the solid organics/ice interface (see text for model details). Operating wavelengths for this proposed Cassini radar system are 2.2 and 13.6 cm; the longer wavelength could possibly sound the ocean floor, provided the (poorly understood) absorption of polar solutes is sufficiently low.